

Electromagnetic Form Factors of the Pion, Kaon, and Proton at $Q^2 = 13.48 \text{ GeV}^2$

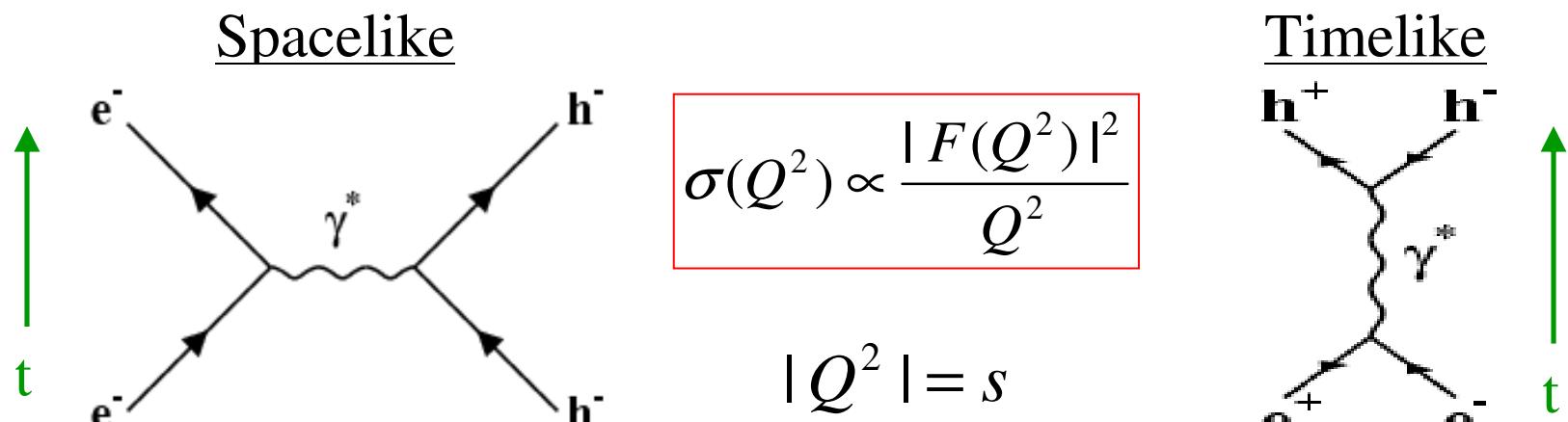
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Introduction

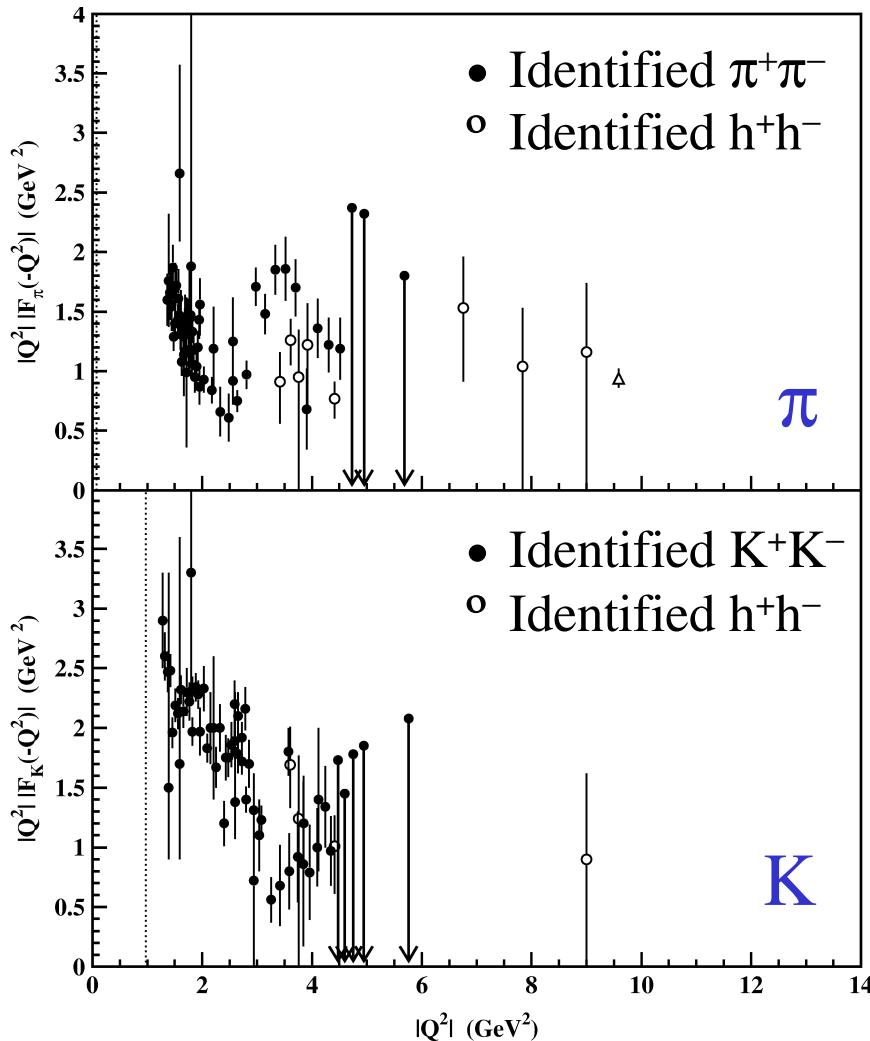
Hadronic Electromagnetic (EM) Form Factors allow us
an opportunity to study the underlying quark structure



Perturbative QCD (pQCD) (PRL 31, 1153 (1973),
PRD 22, 2157 (1980))

Mesons: $|F(Q^2)| \propto \frac{\alpha_s(Q^2)}{Q^2}$ Baryons: $|F(Q^2)| \propto \frac{\alpha_s^2(Q^2)}{Q^4}$

Experimental Status: Pion and Kaon



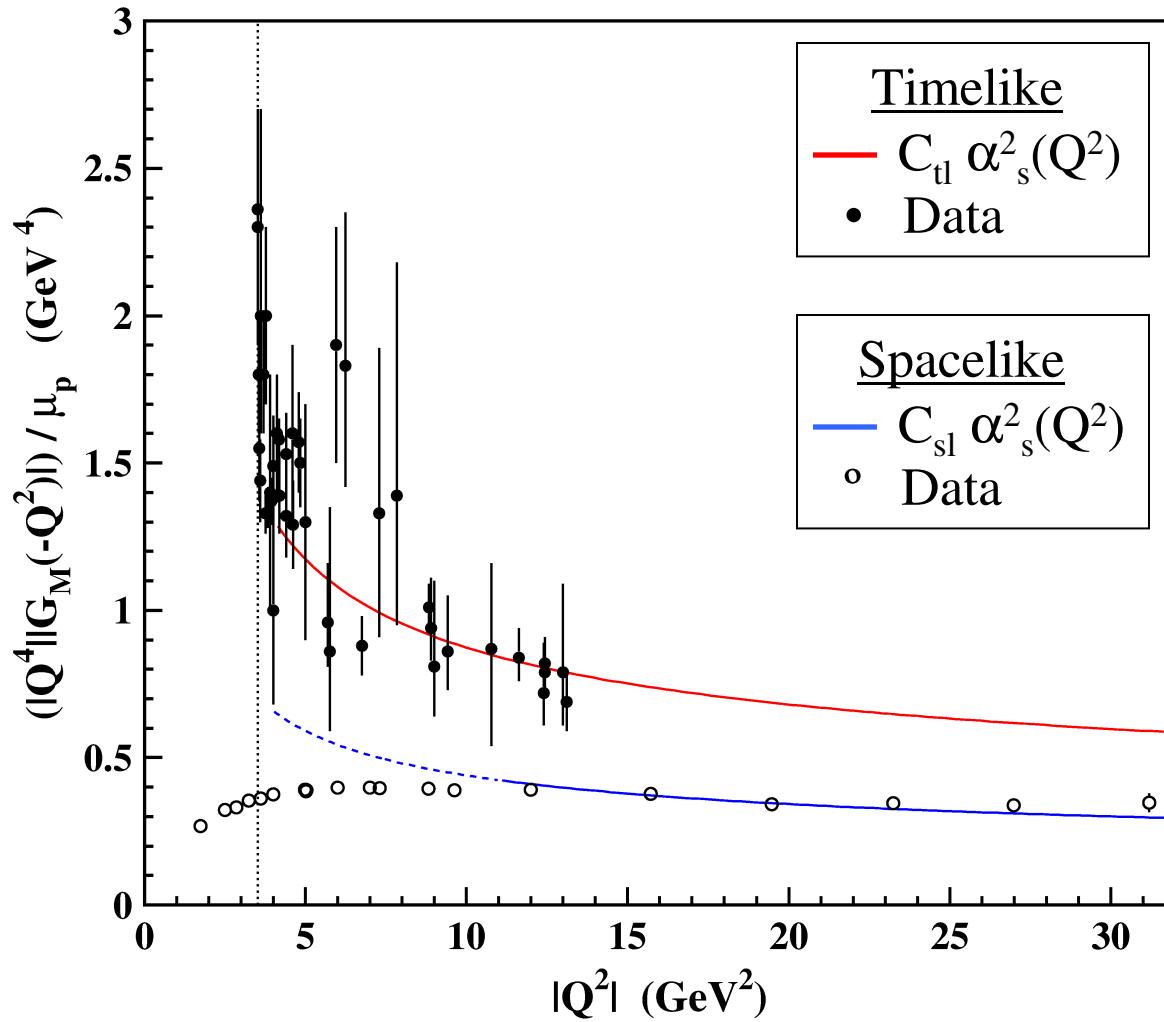
Only existing data with $|Q^2| > 4.5$ GeV 2 could not directly identify π^\pm and K^\pm

(Lett. Nuovo Cim. 14, 418 (1975), PLB 46, 261 (1973))

- Observed $e^+ e^- \rightarrow h^+ h^-$
- $h^+ h^-$ is interpreted as 45% $\pi^+ \pi^-$ and 55% $K^+ K^-$

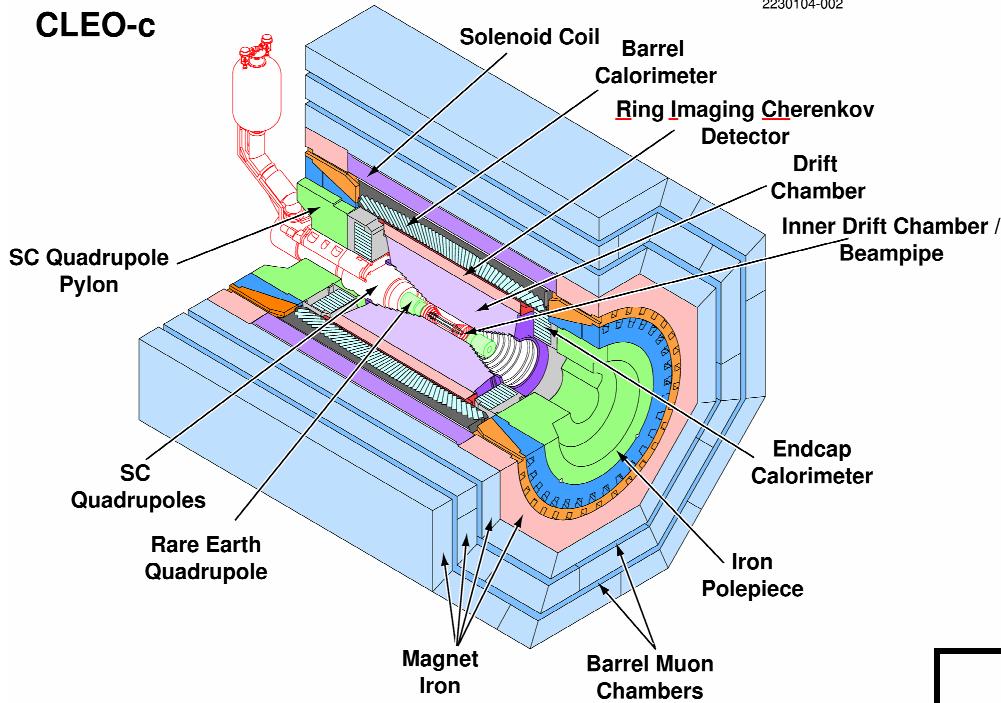
These poor data was used in the much publicized controversy between Brodsky et al. and Isgur/Llewellyn Smith concerning the onset of pQCD

Experimental Status: Proton



There is a factor 2 difference between timelike and spacelike $|G_M^P(Q^2)|$

CLEO-c Detector & Data Sample

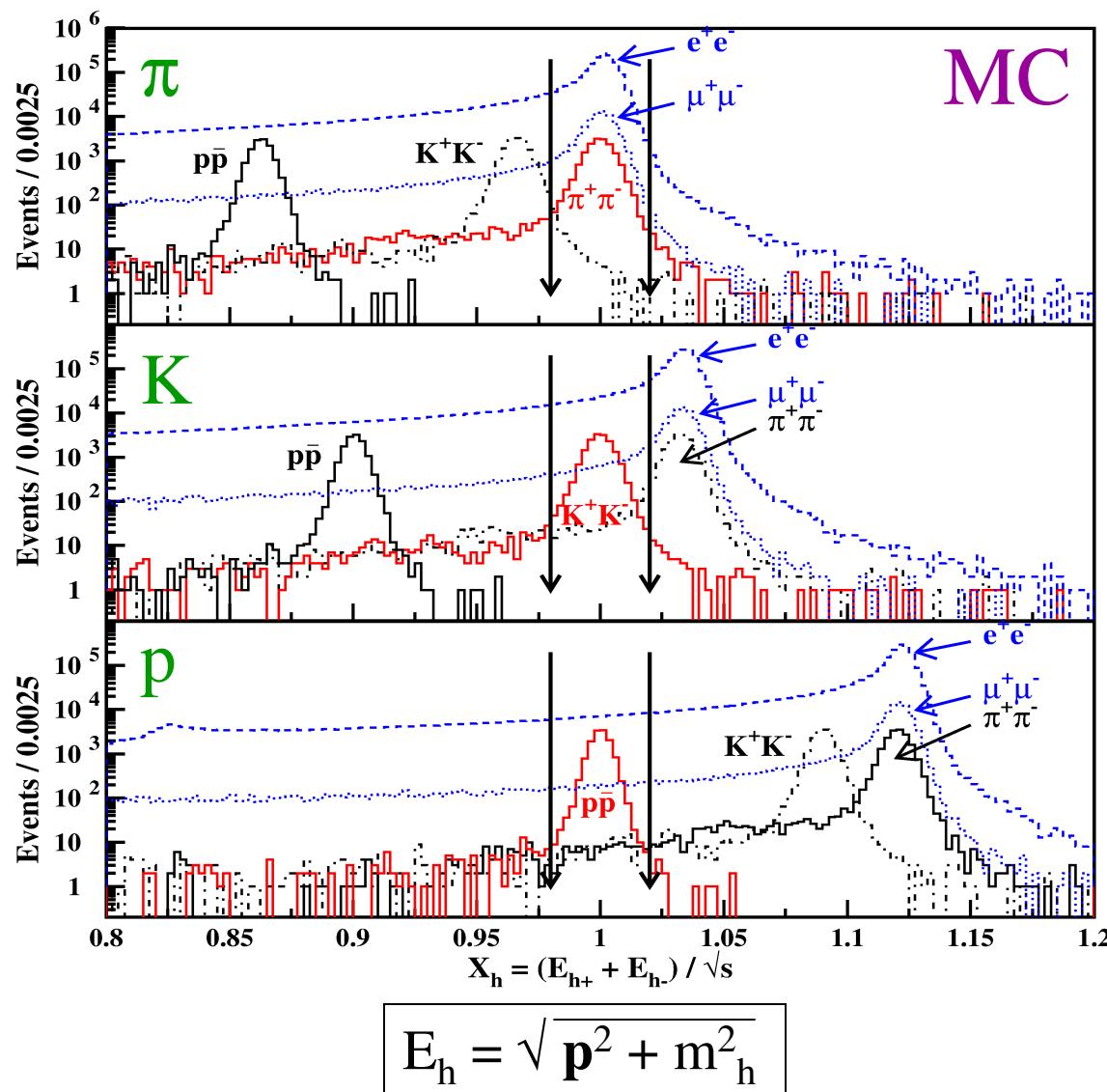


- Tracking and calorimeter system covers ~93% of solid angle
- Track Resolution
 - 0.6% at $p = 1 \text{ GeV}$
- RICH detector covers ~80% of solid angle
- Good separation/identification of e , μ , π , K , and p

Use # of observed $\pi^+\pi^- J/\psi$ events in $\Psi(2S)$ & $\sqrt{s} = 3.671 \text{ GeV}$ data samples to determine $\Psi(2S)$ tail at $\sqrt{s} = 3.671 \text{ GeV}$ (PRL 94, 232002 (2005))

	15 MeV below $\Psi(2S)$	$\Psi(2S)$
$\sqrt{s} (\text{GeV})$	3.671	3.686
$L (\text{pb}^{-1})$	20.7	2.89

Event Selection

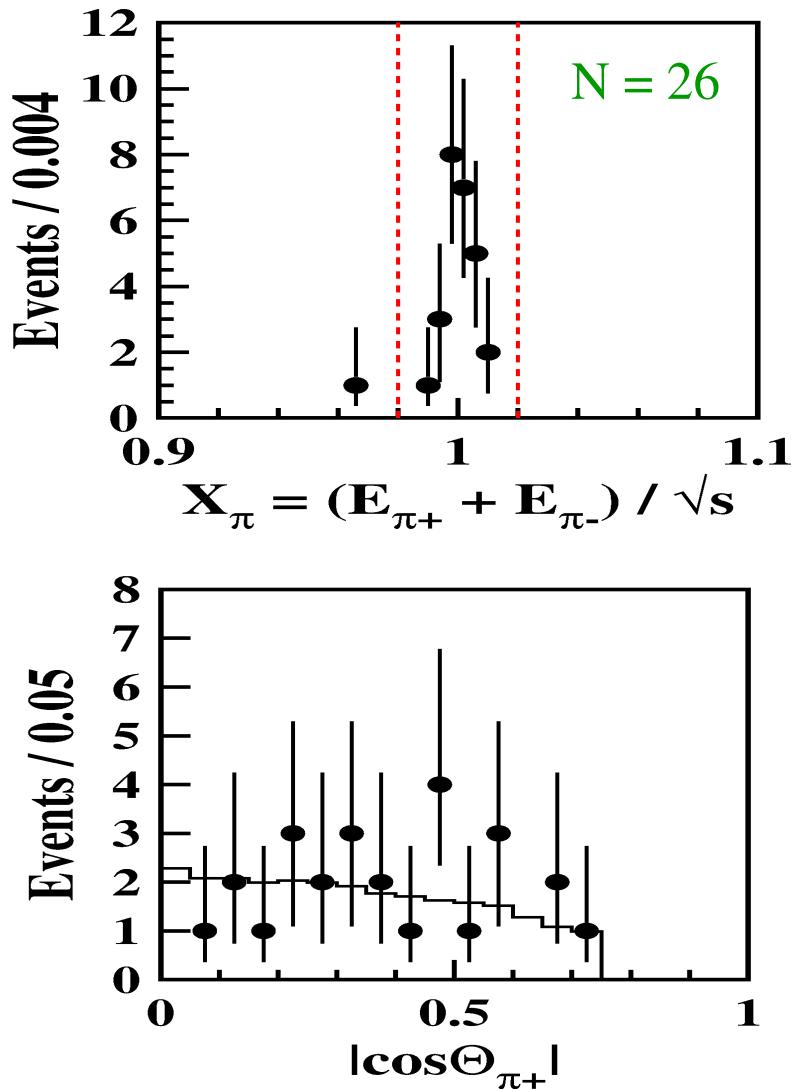


- Two good tracks
- Net charge = 0

Use dE/dx and RICH
to distinguish

- $\pi/e, \pi/K$
 $(\pi/\mu \text{ not possible})$
 - $K/e, K/\mu, K/\pi$
 - $p/e, p/\mu, p/\pi$
-
- $E_{CC}/p < 0.85$
(except for \bar{p} track)
 - $E_{CC} > 420 \text{ MeV}$ for π

$e^+e^- \rightarrow \pi^+\pi^-$



$N(\ell^+\ell^-) \sim 0.1 \quad N(\psi(2S) \text{ tail}) < 0.1$

$$N(e^+e^- \rightarrow \pi^+\pi^-) = 25.9 \pm 5.1$$

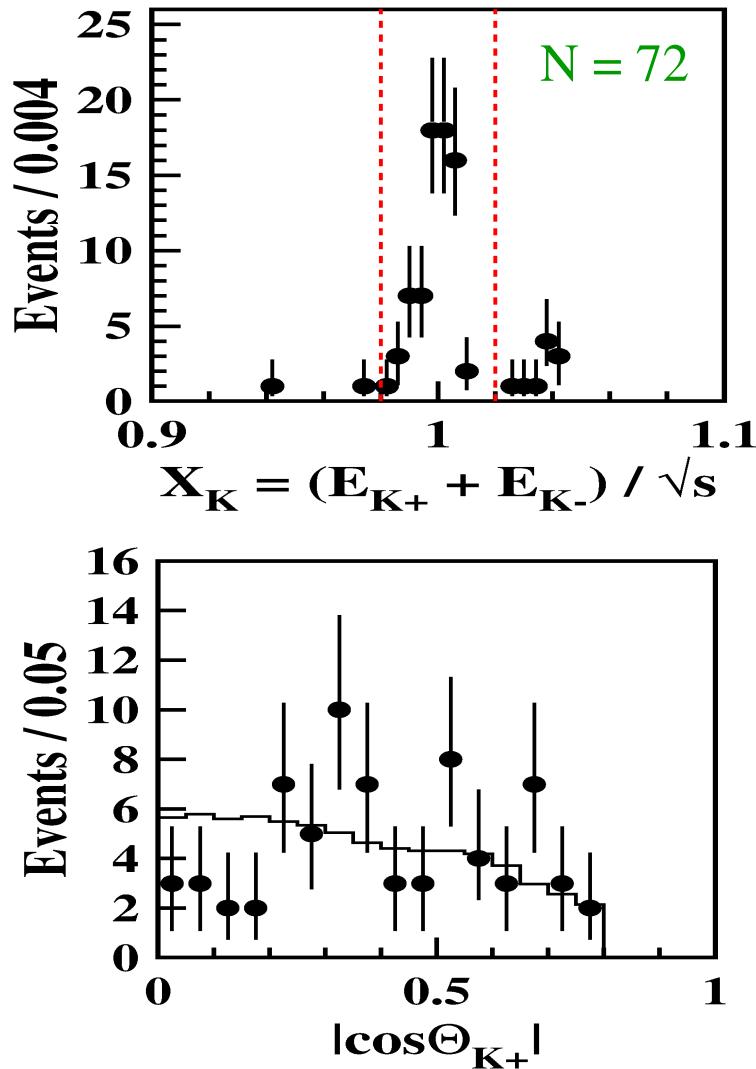
$\sigma(e^+e^- \rightarrow \pi^+\pi^-) =$
 $9.0 \pm 1.8(\text{stat}) \pm 1.3(\text{syst}) \text{ pb}$
 Includes Radiative Corrections

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} \beta_\pi^3 |F_\pi(s)|^2 \sin^2 \theta$$

$|F_\pi(13.48 \text{ GeV}^2)| =$
 $0.075 \pm 0.008(\text{stat}) \pm 0.005(\text{syst})$

First precision measurement
 with $Q^2 > 4.5 \text{ GeV}^2$

$e^+e^- \rightarrow K^+K^-$



$$N(\ell^+\ell^-) = 0.6 \pm 0.2$$

$$N(\psi(2S) \text{ tail}) = 0.6 \pm 0.1$$

$$N(e^+e^- \rightarrow K^+K^-) = 70.9 \pm 8.5$$

$$\sigma(e^+e^- \rightarrow K^+K^-) = \\ 5.7 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \text{ pb}$$

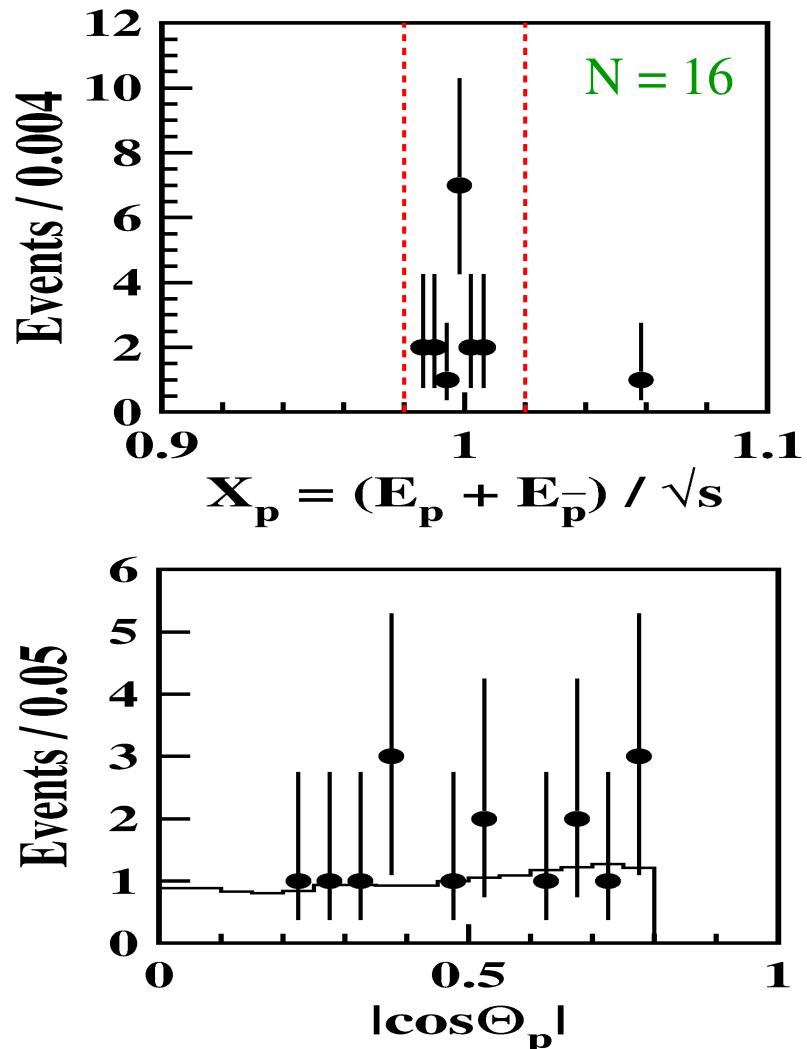
Includes Radiative Corrections

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} \beta_K^3 |F_K(s)|^2 \sin^2 \theta$$

$$|F_K(13.48 \text{ GeV}^2)| = \\ 0.063 \pm 0.004(\text{stat}) \pm 0.001(\text{syst})$$

First precision measurement
with $Q^2 > 4.5 \text{ GeV}^2$

$e^+e^- \rightarrow p\bar{p}$



$$N(\ell^+\ell^-) < 0.1 \quad N(\psi(2S) \text{ tail}) = 1.9 \pm 0.2$$

$$N(e^+e^- \rightarrow p\bar{p}) = 14.1 \pm 4.8$$

$$\sigma(e^+e^- \rightarrow p\bar{p}) = \\ 1.2 \pm 0.4(\text{stat}) \pm 0.1(\text{syst}) \text{ pb}$$

Includes Radiative Corrections

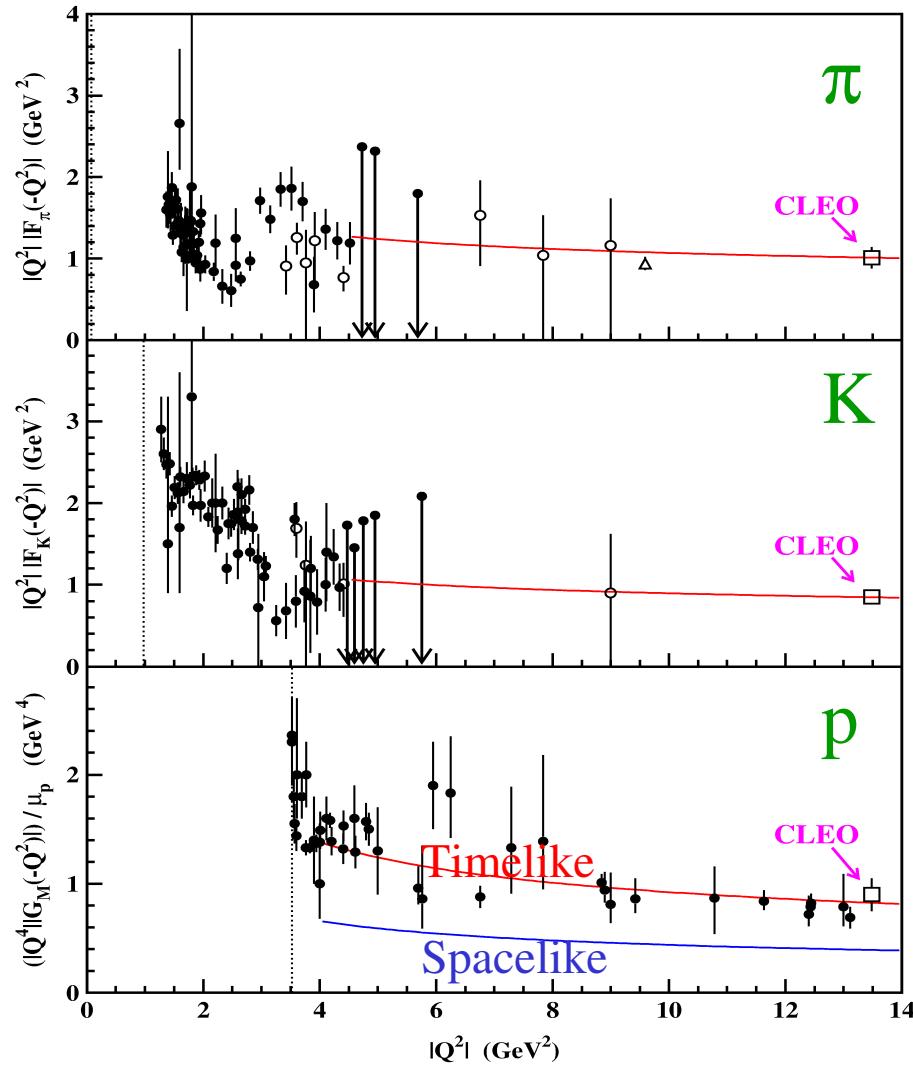
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \beta_p \left[|G_M^P(s)|^2 (1 + \cos^2 \theta) \right. \\ \left. + \frac{4m_p^2}{s} |G_E^P(s)|^2 \sin^2 \theta \right]$$

$$|G_M^P(13.48 \text{ GeV}^2)| = \\ 0.014 \pm 0.002(\text{stat}) \pm 0.001(\text{syst})$$

Assuming $|G_E^P| = |G_M^P|$

$$|G_M^P(13.1 \text{ GeV}^2)| = 0.0112 \pm 0.0017 \\ [\text{FNAL E835: PRD 60, 032002 (1999)}]$$

EM Form Factor Results



Pion & Kaon EM Form Factors
are the first direct measurements
with $Q^2 > 4.5$ GeV 2

Proton EM Form Factor
consistent with existing data

Summary

Using the $L(e^+e^-) = 20.7 \text{ pb}^{-1}$ data sample at $\sqrt{s} = 3.671 \text{ GeV}$ taken with the CLEO-c detector:

$$|F_\pi(13.48 \text{ GeV}^2)| = 0.075 \pm 0.008(\text{stat}) \pm 0.005(\text{syst})$$

$$|F_K(13.48 \text{ GeV}^2)| = 0.063 \pm 0.004(\text{stat}) \pm 0.001(\text{syst})$$

$$|G_M^P(13.48 \text{ GeV}^2)| = 0.014 \pm 0.002(\text{stat}) \pm 0.001(\text{syst})$$

(Assuming $|G_E^P| = |G_M^P|$)

pQCD prediction: $\frac{|F_\pi(Q^2)|}{|F_K(Q^2)|} \xrightarrow{Q^2 \rightarrow \infty} \frac{f_\pi^2}{f_K^2} = 0.67 \pm 0.01$

(PLB 87, 359 (1979),
PLB 94, 245 (1980))

This analysis: $\frac{|F_\pi(13.48 \text{ GeV}^2)|}{|F_K(13.48 \text{ GeV}^2)|} = 1.19 \pm 0.17$